The Effect of Local Site Conditions on Recorded Strong Earthquake Motions

by Paul C. Jennings*

INTRODUCTION

The subject of the effects of local soil conditions on strong ground motion is of particular interest now because of efforts underway to modify the building codes, new legislation concerning the aseismic design of hospitals, problems of earthquake-resistant design of nuclear power plants and a generally increasing sophistication of earthquake-resistant design procedures in structural engineering practice. As a result of these factors, many major projects now require geological and seismological studies, including some assessment of the expected earthquake motion at the site and an estimate of any probable effects of local site conditions on the expected motions.

It is obviously important to identify those characteristics of ground motion that may be determined by local site conditions in a predictable manner, and to incorporate the predictable effects into the state of the art by modification of codes and by development of suitable calculation techniques. It is equally important, of course, not to go so far in this direction that vague or contradictory concepts not yet resolved by measurements become parts of codes and standard practices.

At the present time, there is a wide spectrum of technical opinion regarding the confidence with which the characteristics of any potential site effects can be calculated for the type of conditions encountered in the

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United States, particularly in California. It is known that if local soils are sufficiently soft and deep, such as at Mexico City and at some locations in Japan, marked effects on earthquake motions can occur, whereas on rock or very firm alluvium there is general agreement that local effects are insignificant with respect to effects of the mechanism of the source of the motions and the effects of the paths by which the waves reach the site. The general nature of the problem of determining the effect of source mechanism, travel path, and local site conditions is illustrated by Figure 1. The disagreement among engineers and scientists on this topic is not over the fact that seismic waves travel through the ground and interact with certain features of local geology, but concerns the circumstances under which site effects occur in a predictable manner, and the adequacy of simple models for calculating potential effects. The shorter-period components of the seismic waves, which are of principal importance for engineering, are strongly affected by inhomogeneities in rock and soil, consequently earthquake motions near the surface of the ground are complex and not well understood.

There is a wide difference in the results of studies to determine ground motion for design by means of simplified calculations when done for equivalent sites by different consultants. Although the differences are less when more experienced parties are involved, differences of a factor of two or more are not uncommon in practice, and maximum differences of design spectra reported to the Los Angeles Building Department range up to a factor of four over some parts of the spectrum. This is taken as empirical evidence that, quite aside from accuracy, the calculation methods have not yet reached the desired consistency.

In this discussion, I want to concentrate on actual measurements of strong earthquake motions obtained in southern California, independent of calculations or qualitative assertions. The data are drawn primarily from three of the references listed at the end of this article. (Hudson, 1972; Udwadia and Trifunac, 1973; and Crouse, 1973). Although the results and conclusions should apply to some degree to comparable conditions elsewhere, such extrapolations should be done cautiously because the soils in southern California are firmer than those in many other areas, such as some of the softer materials in the San Francisco Bay area, for example.

MEASUREMENTS IN THE PASADENA AREA

The Pasadena area is one of the most heavily instrumented regions in the United States, and the strong ground motions recorded there during the San Fernando earthquake offer an almost unequalled chance to study the way strong shaking can vary over an area of this size, and to seek correlations with properties of the recording sites. Figure 2 (Hudson, 1972) shows the general plan of the area, its location with respect to the epicenter, and the location of the accelerometers and seismoscopes. Also shown are the general geologic properties, including type of rock and depth of alluvium. There were four accelerometers and nineteen seismoscopes that recorded motions during the earthquake. The maximum response of the seismoscopes and the direction of maximum response are also included in Figure 2. It should be recalled that the seismoscope has a natural period of 0.75 secs and damping of 10% of critical, so that it represents a system with dynamic properties quite similar to those of the fundamental mode of a strongly vibrating building in the 7- to 15-story range (depending on type of construction). The general level of ground shaking in the Pasadena area was in the 10-20%g range, strong enough to cause significant nonstructural damage to many buildings, and structural damage to a few old buildings designed before 1933.

As seen in Figure 2, the Pasadena area is small enough, and far enough away from the epicenter so that variations in the intensity of motion over the area because of distance should be rather small. It is interesting to observe from Figure 2 that the largest response (ER) is on rock, whereas the smallest responses are on 1200 ft of alluvium (HES), on an outcrop of rock (WJS) and on 400 ft of alluvium (DG). Another large maximum response occurred on 800 ft of alluvium (MS), but many alluvial sites on various depths (EW, SMC, CR, VT, GES, NM, FP and RG) showed about the same maximum response as that which occurred on rock at the Seismological Laboratory (SL). This lack of correlation with local conditions was seen also in the accelerograms measured at the Jet Propulsion Laboratory (JPL), the campus (ML and ATH) and at the Seismological Laboratory (SL). Figure 3 shows a comparison of two of the spectra (SL and ATH) in which it is seen that over the majority of periods the E-W motion at the Seismological Laboratory (on rock) produced stronger response than either component of the motion at the Athenaeum (on 900 ft of alluvium). It is seen also that the E-W motion at the Seismological Laboratory was two to three times as strong as the N-S motion over most of the spectrum. The other two accelerometers (ML and JPL) showed strength of motions of about the level of the E-W motions of Figure 3, with some significant variations (Hudson, 1972). There are no peaks in the spectra that can be related clearly to site effects.

It is hard to see in these data any justification for asserting that shaking is stronger on alluvium than on rock, or that the strength of shaking in any portion of the spectrum is correlated in a predictable manner with local site conditions. The general impression is one of complexity, rather than simplicity, and it would be most appropriate in the face of this complexity to use a single design spectrum for the entire area until additional data indicated otherwise.

The implications of Figure 2 are even more important when it is realized that many of the recording sites were those occupied by Gutenberg (1957) in an earlier study of the effects of local site conditions on very small earthquake motions. In that study, for example, Gutenberg found that on the average the amplitude of motions on the campus on 900 ft of alluvium were three to four times those recorded on rock at the Seismological Laboratory. The study by Gutenberg has had a large influence on efforts for seismic zoning and microzonation, and it is therefore important to realize that the effects measured at very small motions were found not to occur, in the San Fernando earthquake, at least, when strong ground motions were recorded.

MEASUREMENTS AT EL CENTRO

It is well known that strong ground motion was recorded at El Centro in 1940 and 1934, but it is perhaps not as widely known that many other ground motions strong enough to give usable acceleration records have also been recorded there. A study of 15 accelerograms (three components each) obtained at the El Centro site (Udwadia and Trifunac, 1973) presents some valuable data regarding the relative effects of source mechanisms, travel paths and site conditions on the characteristics of strong ground motion.

The frequency content of the accelerograms was examined by means of Fourier spectra, which are somewhat more sensitive for this purpose than the undamped response spectrum curves. When the Fourier spectra from all 15 earthquakes were compared it was concluded that there were no recurrent periods in the motions; the spectral peaks varied from earthquake to earthquake, and could not be construed as being characteristic of local site conditions.

An example of these results is given in Figure 4. In the upper part of the figure, events 55.3, 55.4 and 55.5 all have the same epicenter, and therefore the same travel path and, of course, local site conditions, yet it is clear that the frequency content of the motion is quite different. This is interpreted as reflecting differences in the source mechanisms. The lower part of Figure 4 includes the N-S components of the strong shaking recorded in 1940 and in 1934, among others. The frequency content of the two strong records is similar in a general way, but there are no strong peaks that match particularly well. The overall conclusions from results such as shown in Figure 4 is that for the accelerations recorded at El Centro, any local site effects have been overshadowed by effects of travel path and source mechanism. An additional conclusion is that the concept of a predominant period for the El Centro site is inappropriate for there is no significant characteristic in the accelerograms or the spectra that can be identified as a natural period of the site. It should be pointed out that the Fourier techniques applied to the strong-motion records are the same used in studying data from ambient tests of building structures excited by wind. In the case of wind-excited buildings, the fundamental frequencies are easily found and usually four or more modes of each type (e.g., N-S, E-W and torsion) can be identified from predominant peaks in the spectra.

The simplified method of calculating surface ground motions by considering a column of soil to be excited by "bedrock" motion at its base corresponds exactly to the method of calculating the roof response of a multistory building when the base motion is given. The soil column is conceived to have shearing deformations, like a building, and the methods of computing the response are the same for the soil column and the building. It has been demonstrated that this calculation method gives good results for buildings, that is, the calculated roof motion agrees well with motion actually recorded on the roof. If the method of calculating ground motions by means of a soil column is correct, then motions recorded on alluvium should have characteristics similar to motions recorded on the roofs of multistory buildings. The spectra of roof motions show prominent peaks at the natural periods of vibration of the building. Such peaks are not found, in general, in spectra of ground motions, except in special cases like Mexico City. If, at particular sites, such prominent peaks do occur in the spectra and can be identified with the natural periods of the soil mass, then the simplified analysis using the soil column should give good results. If the natural periods of the soil mass cannot be identified on the spectra, then the simplified model of a soil column is not appropriate, and cannot be expected to give good results. Nearly all strong ground motions recorded in California have spectra that do not show prominent peaks that can be identified as natural periods of the soil.

In their study, Udwadia and Trifunac also presented the results of microtremor studies of the El Centro area. Their data show that this approach is not a reliable method of assessing expected earthquake motions, inasmuch as the frequency content of the motion changed from one day to the next, the relative frequency content was different from that shown by the accelerograms of earthquake motion, and the peaks of the Fourier spectra of the microtremors bore no obvious correlation with peaks on the Fourier spectra of the accelerograms. Until the reliability of microtremor studies can be established, design criteria extrapolated from such studies must be viewed skeptically.

MEASUREMENTS FROM THE SAN FERNANDO EARTHQUAKE

Distribution of peak acceleration.

The use of peak acceleration as a rule-of-thumb for identifying the strength of an accelerogram is a long-standing practice in earthquake engineering, and although it is often stated by those knowledgeable in the field that this is a crude measurement, it often is used as a precise measure by engineers and geologists not so familiar with accelerograms and spectra. The variation in peak accelerations in the San Fernando earthquake is shown in Figure 5 in which it is apparent that the peak accelerations can easily vary a factor of two for records obtained quite close to one another. There are two reasons for these variations. The first is that there are real variations in the strength of the motion over relatively short distances in some cases, and the second is that in other cases the variation of the peak acceleration is larger than is actually the case if the entire spectrum is compared.

Figure 6 shows another comparison using peak acceleration. In this figure it is seen that variations in peak acceleration of a factor of two or more are to be expected at distances of 20 to 40 kilometers ~~miles~~ from the center of the earthquake.

Studies of closely-spaced buildings.

Accelerograms obtained in a group of six closely-spaced buildings on Wilshire Boulevard were studied in a recent thesis at Caltech by C. B. Crouse (1973). The buildings are in the neighborhood of Wilshire and Mariposa (group 8 in Figure 7), are of steel (4) and reinforced concrete construction (2), vary in height between 7 and 39 stories, and all lie within a circle of 1100-ft radius. Five of the six buildings are on alluvium overlying a layer of shale between 30 and 40 ft below the surface, and one of the buildings, 3550 Wilshire, is on alluvium whose depth, though not known exactly, exceeds 90 ft. The rock is a Miocene shale with a density of only 90lb/ft^3.

For the five buildings over the alluvium, the foundations include caissons (2), spread footings (2) and footings with friction piles (1). The building over the 90+ ft of alluvium is on spread footings. For the five buildings on shallow alluvium, the location of the accelerometer recording base motion varied from 35 ft above the surface of the rock to 25 ft below; the record at 3550 Wilshire was obtained 20 ft below the surface of the ground.

The recorded accelerations (E-W only) are shown in Figure 8 and the corresponding response spectra for 2% damping are shown in Figure 9. The similarities in the accelerograms and spectra are obvious, with the spectra showing more similarities than the accelerograms. From the point of view of design, it seems clear that a single design spectrum should be chosen for all of the sites, based on the data from the San Fernando earthquake. It is noted also that the anomalous site at 3550 Wilshire did not produce a record or spectra significantly different from the others; there is no apparent difference in the records or spectra resulting from simply the increased depth of alluvium.

A similar analysis was done for a larger group of buildings centered about the Wilshire-Mariposa group. These buildings are also located in Figure 7. The E-W accelerograms and corresponding spectra are shown in Figures 10 and 11. It is seen in these figures that buildings close together show similarities like those shown by the Wilshire-Mariposa group, but that over this larger circle of radius about 3 miles, the differences are larger than over the smaller circle.

It is interesting to compare the maximum range in spectra of the six buildings of the Wilshire-Mariposa group with the maximum range of spectra for the six buildings of the larger circle. Figure 12 gives this comparison. As would be expected, the range of values over the larger circle of buildings exceeds, in general, that of the smaller circle, but the overall impression is that the two groups have approximately the same spectral shape. There does not seem to be any major differences that could be attributed to local site effects with any degree of confidence. For example, the prominent hump in the spectra near 4-6 seconds and the peaks near one second on the N-S spectra and near 1-1/2 seconds on the E-W spectra seem to be shared by both sets of data.

It can be noted also that if one were choosing the level of a design spectrum of a standard shape for this area based on the two sets of data, there would not be much difference in the levels; the records obtained closer to the earthquake tend to be a little stronger than those more distant, but the effects are not marked.

Shear-beam analysis.

The data for the six buildings at Wilshire-Mariposa indicated that the design spectra for the six sites should be the same even though the foundation conditions and, in one case, the depth of alluvium, are different. The earthquake data can be used to test the applicability of proposed methods for calculating site effects. Since the spectra at the sites are all essentially the same, any calculation method that gives different results for the sites is wrong, or has been wrongly applied.

The first point that comes from such an approach is that any simplified technique giving design criteria that change significantly when the depth of alluvium changes from 30 or 40 ft to over 90 ft would give the wrong result when applied to the Wilshire-Mariposa sites, if the natural tendency to use the boundary between the recent alluvium and the Miocene shale as the "bedrock" level were followed.

Similar difficulties occur when a shear-beam analysis is done for the site (Crouse, 1973), using the shale as the "bedrock" level. Using the accelerogram recorded below the surface of the rock as the input, a shear-beam analysis of the two most dissimilar of the sites underlain by shallow alluvium showed the two calculated surface motions to be essentially the same, and virtually identical to the motion input at the base. (This is because the short soil columns have high natural frequencies). This feature, which is consistent with the data, is shown in Figure 13. When the same type of analysis is done for the 3550 Wilshire site using an assumed "bedrock" depth of 100 ft, the computed surface motion is significantly different (Figure 13). The higher frequencies have been attenuated and the amplitude of the peaks is smaller. This result is consistent with theoretical discussions of the shear-beam method which have stated that the peak acceleration at the surface can be greater for shallow deposits (30-40 ft) than for deeper deposits (100 ft or more) of similar soil, but it is inconsistent with what actually happened during the earthquake. The accelerogram and spectra for 3550 Wilshire are typical of the group of six, and the site recorded the second largest peak acceleration in both horizontal directions.

It must be concluded that such a simplified view of the problem is incorrect. Either, as some have suggested, one should go deeper for "Bedrock," or a more complicated model is required, one, for example, that considers other types of wave propagation or local topography of subsurface strata. Going deeper for "bedrock" has the computational "advantage" that the deeper motion was not measured and can possibly be adjusted to make the surface motions come out consistent with the data. In any event, it is informative to realize how easy it is to get a result inconsistent with what actually happened when the shear-beam approach is applied in a state-of-the-art manner.

CONCLUSIONS

The general picture emerging from study of the data from the San Fernando earthquake and from El Centro is that the problem is more complicated than we had hoped it might be. Simple rules describing the way the motion behaves on rock and alluvium do not seem to hold. Furthermore, the significance of such concepts as "the fundamental period of the soil" are questionable for the sites studied because they cannot be confirmed by measurements of surface motions during strong earthquakes. It is obvious then that such concepts should be applied with caution at sites where there are no recorded accelerograms. The data discussed are all from southern California and are strictly applicable only there. However, the fact that southern California is the only area for which more than a few really strong accelerograms are available, suggests that the apparent simplicity claimed for other areas is more apparent than real.

In studies of data from southern California the strongest correlation of accelerograms and spectra is with separation distance between sites, rather than soil type or epicentral distance (Crouse, 1973), and significant differences in the motions can occur over distances of thousands of feet. Such results indicate the importance of the travel path upon the motions. In addition, studies of El Centro accelerograms and studies of the San Fernando earthquake indicate that the source mechanism plays a prominent role in determining the frequency content of strong ground motions, particularly those of one-second period or longer. Under these circumstances, it seems best to consider a number of alternative approaches to estimating the ground motions at a site in a given circumstance, and to make comparisons with actual records obtained under comparable conditions wherever possible. With the relative influence of several possible effects on the characteristics of ground motions not yet established by measurements, it seems inappropriate to overemphasize the effects of site conditions, particularly when the extensive data from southern California indicate that for many sites the effects of local conditions are either overshadowed by effects of source mechanism and travel path, or are so complicated that simple relations cannot yet be seen.

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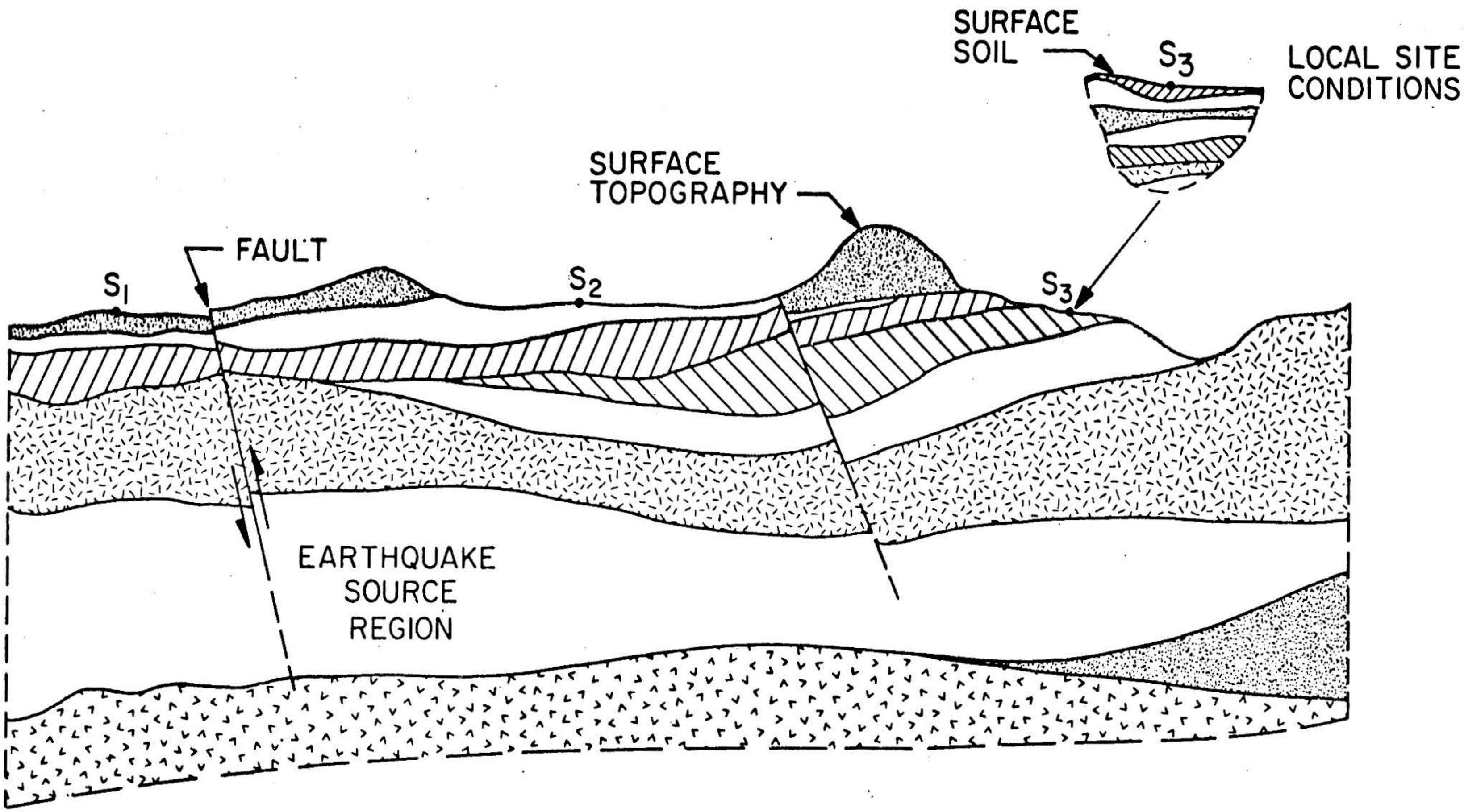
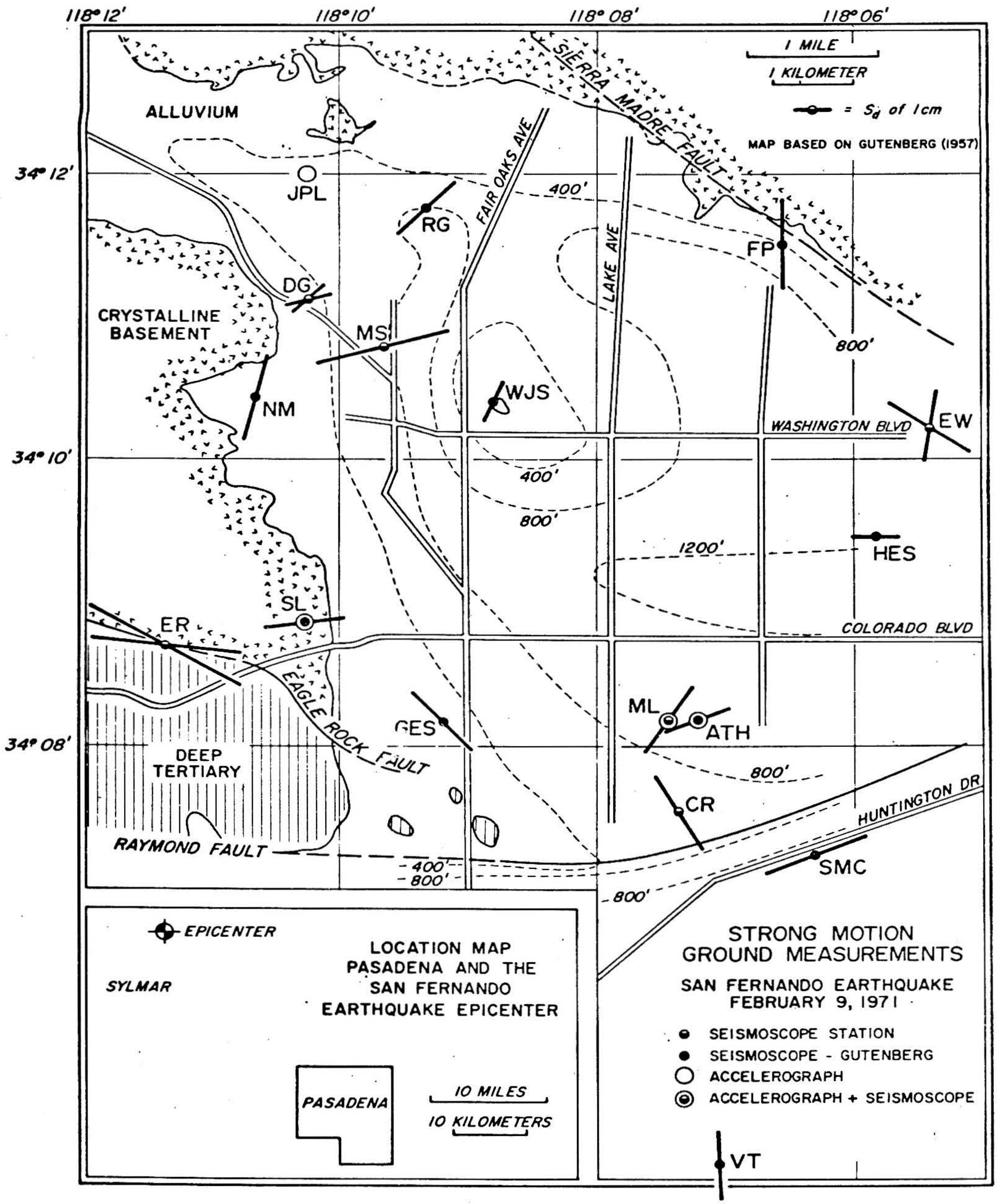
List of Captions

Figure No.	Caption
1	A two-dimensional illustration of the problem of determining the effects of source mechanism, travel path and local site conditions on the characteristics of strong ground motion.
2	Seismoscope responses and accelerograph sites in the Pasadena area during the San Fernando earthquake.
3	Response spectra (ωS_D) of the records obtained at the Seismological Laboratory (SL) and the Caltech Athenaeum (ATH) during the San Fernando earthquake.
4	Fourier spectra of strong-motion accelerograms recorded at El Centro, California.
5	Distribution of peak accelerations recorded during the San Fernando earthquake.
6	Plot of recorded peak accelerations on rock and alluvium as a function of distance from the center of energy release. San Fernando earthquake.
7	Accelerograph locations in western and central Los Angeles during the San Fernando earthquake.
8	Accelerograms (E-W) recorded in the group of six buildings at Wilshire and Mariposa (Location 8 in Figure 7).
9	Response spectra for the E-W accelerograms recorded in the Wilshire-Mariposa group.
10	Accelerograms (E-W) recorded in western and central Los Angeles. (Locations 1-7 in Figure 7).
11	Response spectra for the E-W accelerograms shown in Figure 10.
12	Maximum and minimum response spectra for the Wilshire-Mariposa group (dashed lines) and the more distant buildings (solid lines).
13	Calculated response of soil columns. 3470 Wilshire and 3407 W. Sixth are sites where shallow alluvium (30-40 ft) overlays Miocene shale (bedrock). The base motion at 3550 Wilshire was input at a depth of 100 ft.



SCHEMATIC DIAGRAM SHOWING EARTHQUAKE SOURCE REGION, TRANSMISSION PATH, AND LOCAL SITE CONDITIONS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118° 10'
118° 08'
118° 06'
34° 12'
34° 10'
34° 08'
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1 KILOMETER
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MAP BASED ON GUTENBERG (1957)
ALLUVIUM
SIERRA MADRE FAULT
JPL
RG
FAIR OAKS AVE
LAKE AVE
FP
DG
MS
CRYSTALLINE BASEMENT
NM
WJS
WASHINGTON BLVD
EW
400'
800'
1200'
HES
SL
ER
COLORADO BLVD
EAGLE ROCK FAULT
GES
ML
ATH
DEEP TERTIARY
CR
HUNTINGTON DR
RAYMOND FAULT
SMC
EPICENTER
SYLMAR
LOCATION MAP PASADENA AND THE SAN FERNANDO EARTHQUAKE EPICENTER
PASADENA
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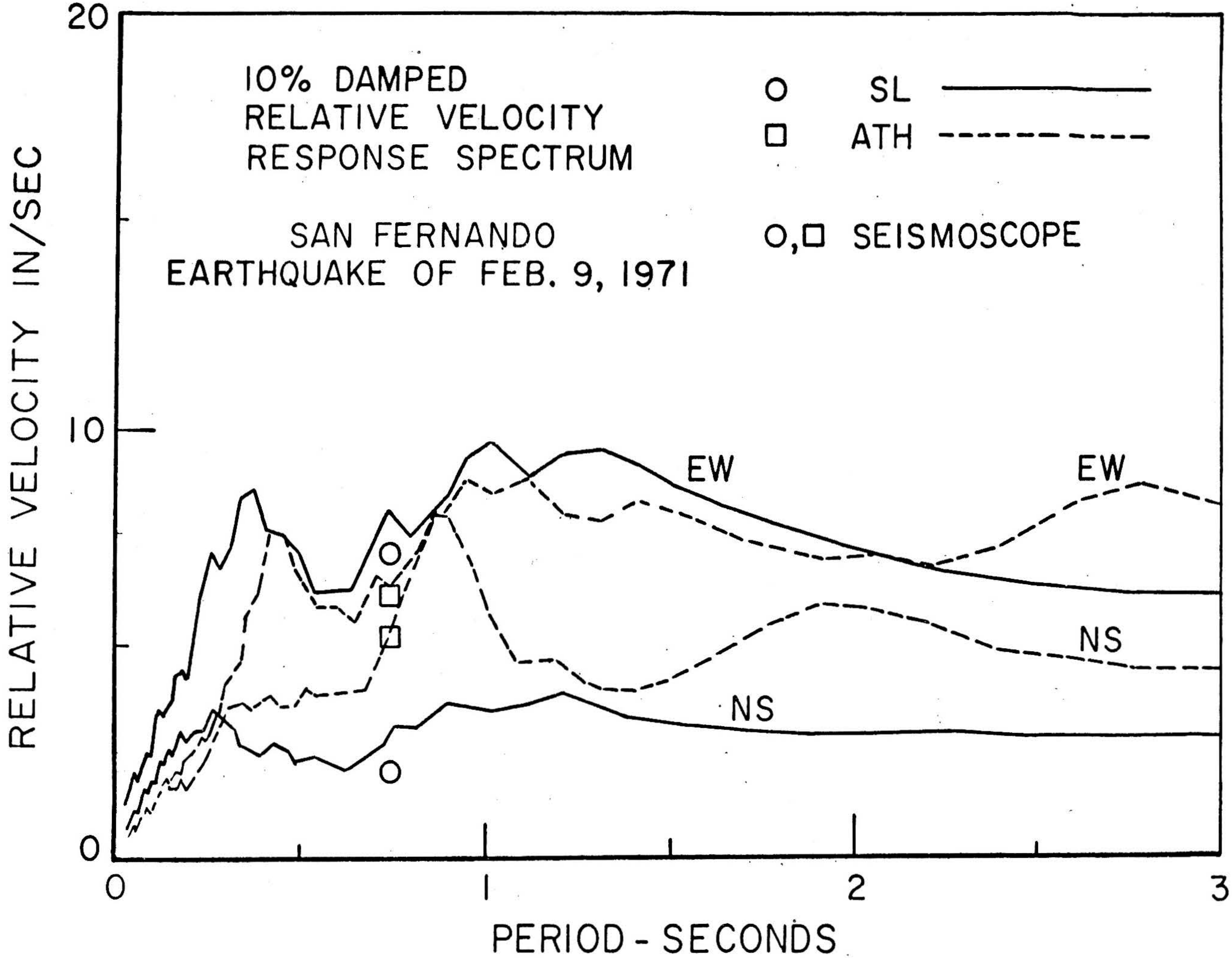
10 KILOMETERS
STRONG MOTION GROUND MEASUREMENTS
SAN FERNANDO EARTHQUAKE FEBRUARY 9, 1971
SEISMOSCOPE STATION
SEISMOSCOPE - GUTENBERG
ACCELEROGRAPH
ACCELEROGRAPH + SEISMOSCOPE
VT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EARTHQUAKE OF FEB. 9, 1971
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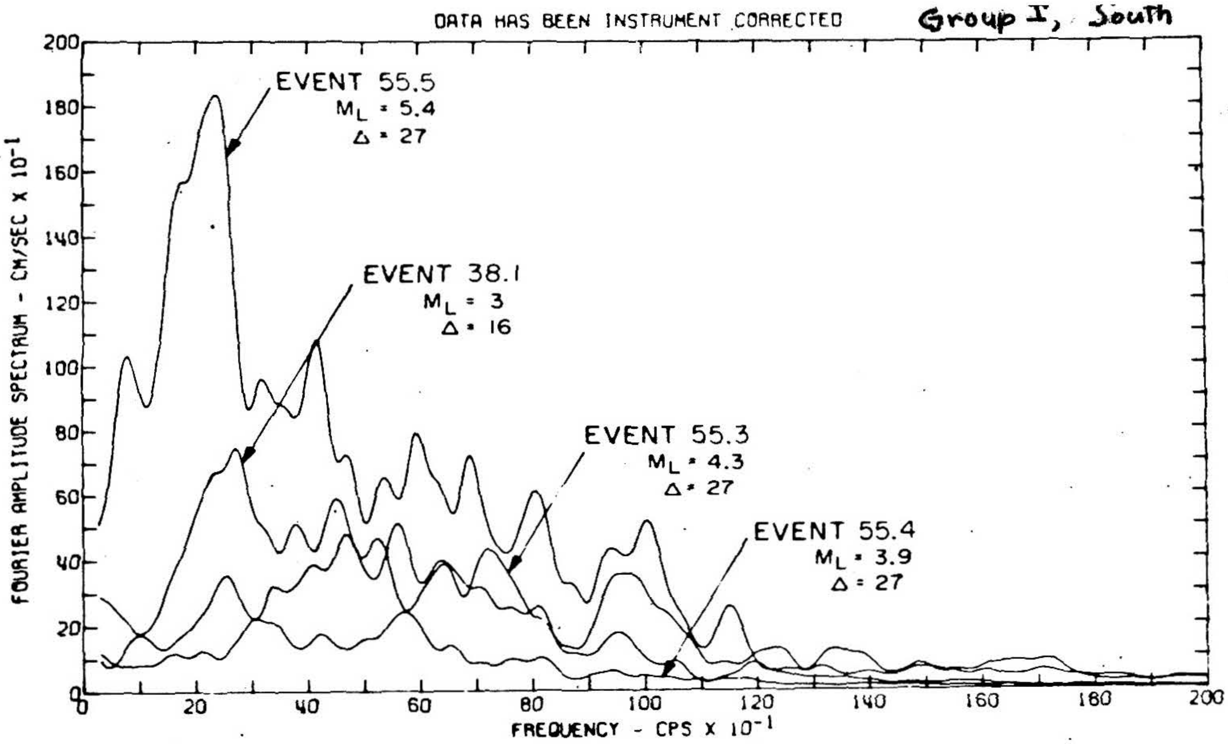


FOURIER AMPLITUDE SPECTRUM OF ACCELERATION

SMOOTHED SPECTRA OF GROUP III ACCELEROGRAMS. SOUTH COMPONENT

DATA HAS BEEN INSTRUMENT CORRECTED

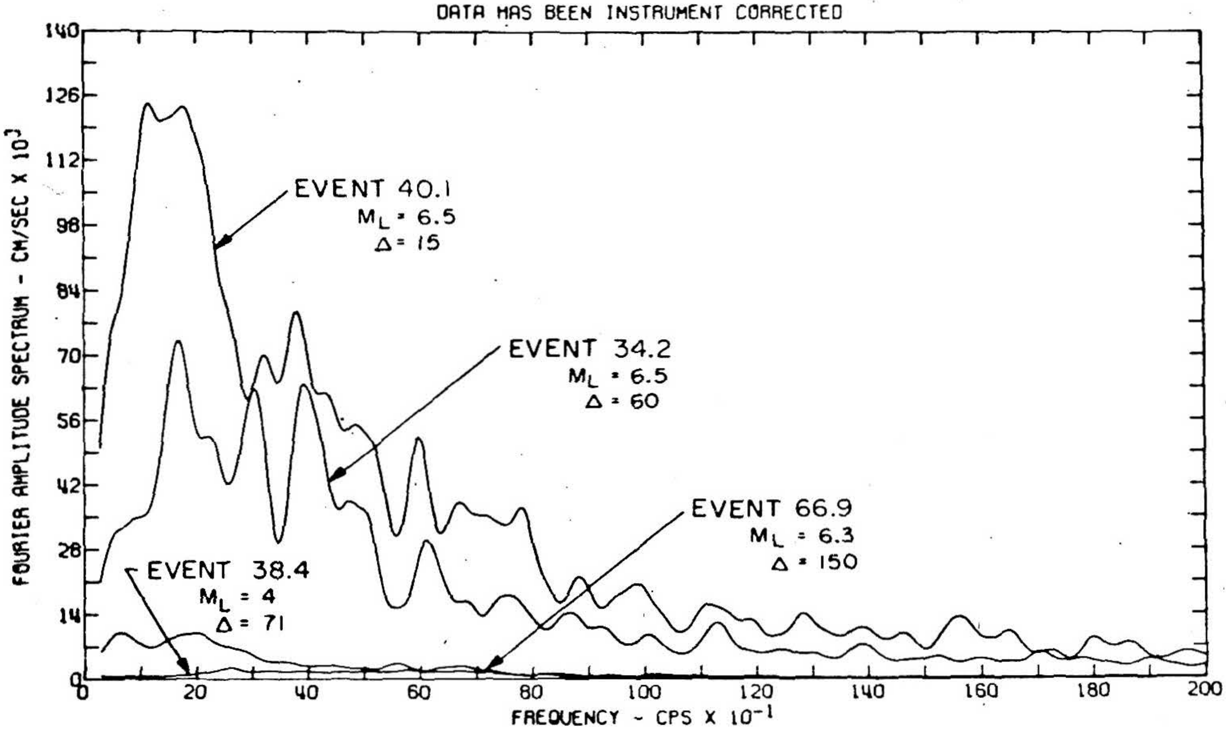
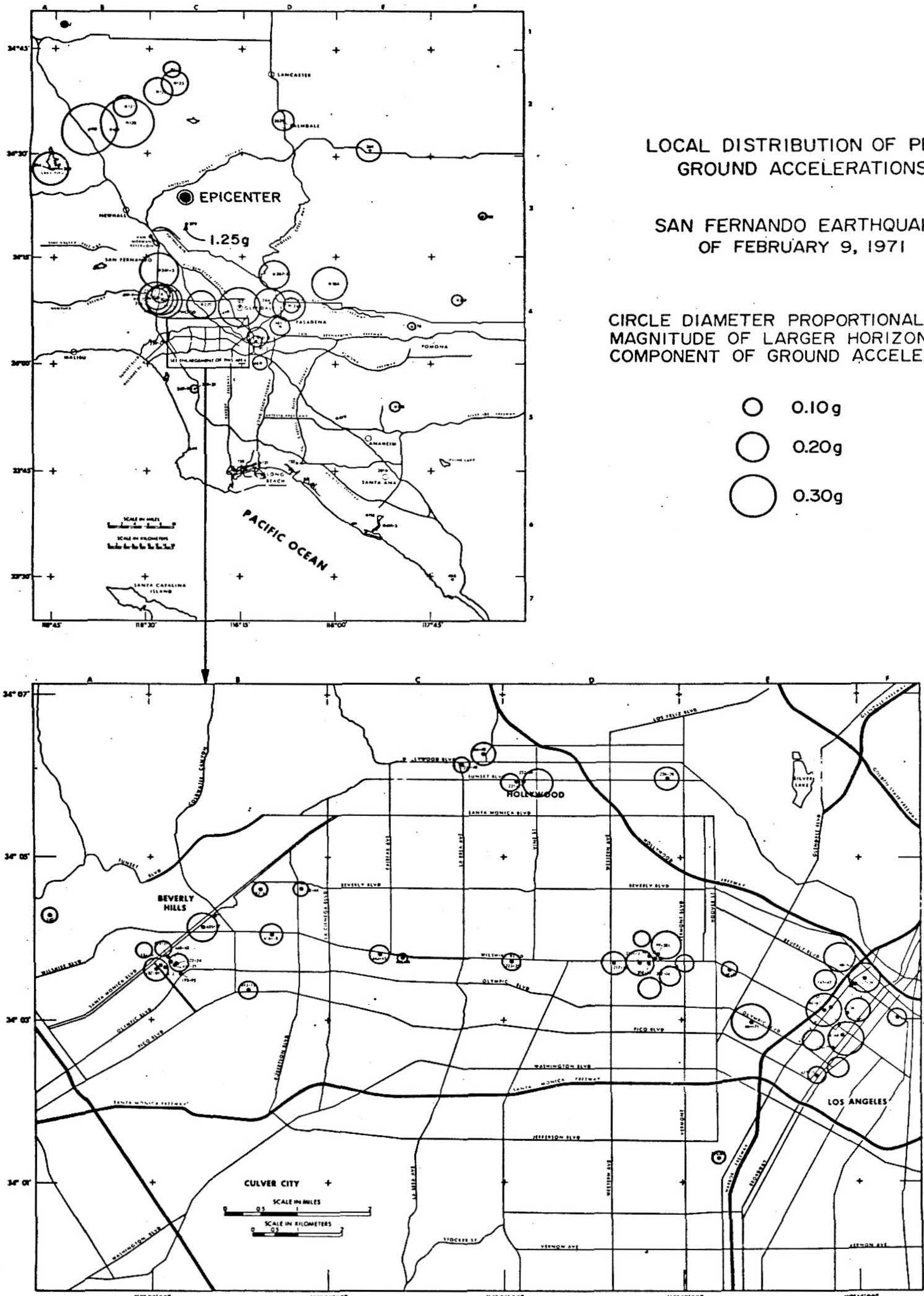


FIG. 4



LOCAL DISTRIBUTION OF PEAK GROUND ACCELERATIONS

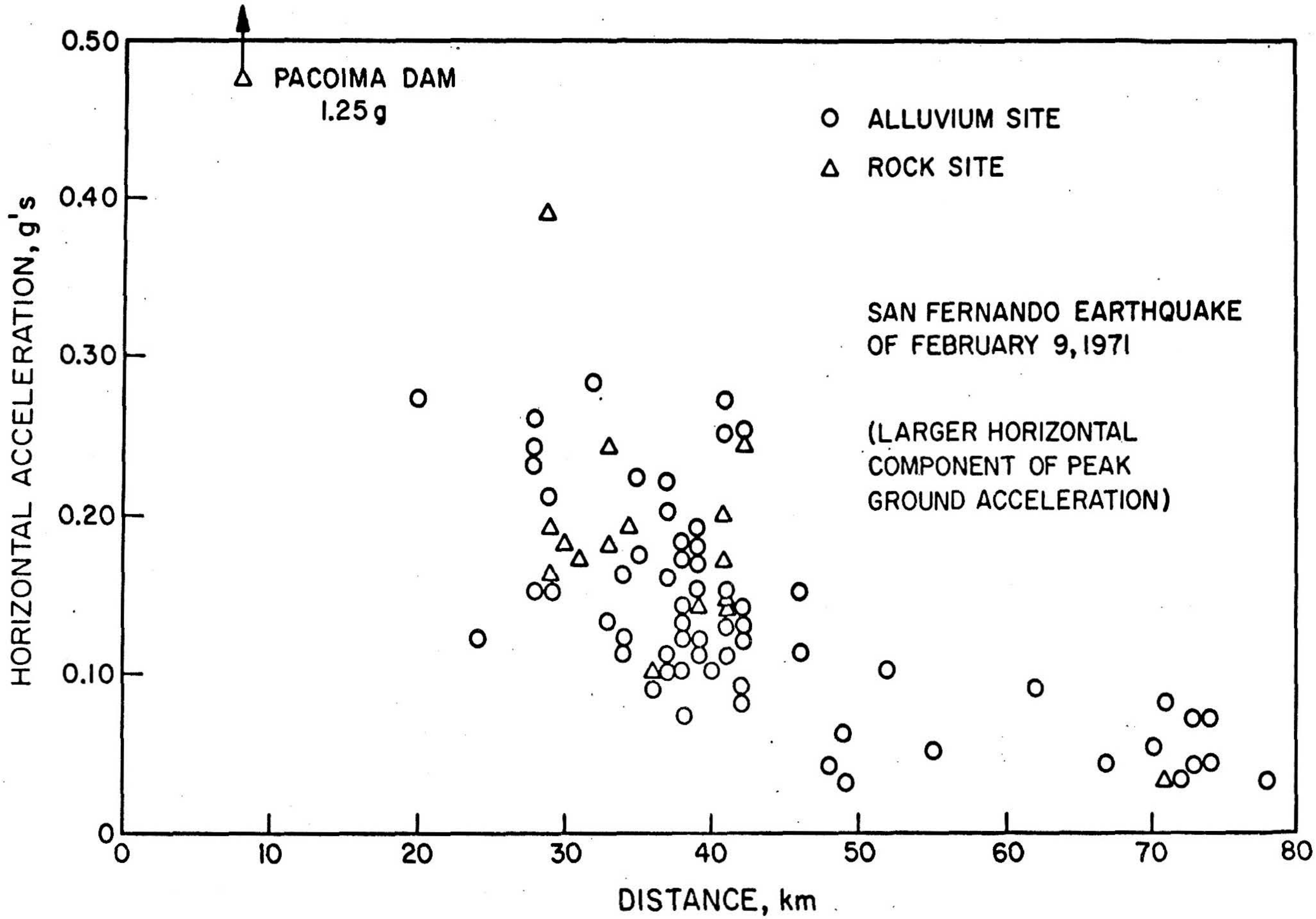
SAN FERNANDO EARTHQUAKE OF FEBRUARY 9, 1971

CIRCLE DIAMETER PROPORTIONAL TO MAGNITUDE OF LARGER HORIZONTAL COMPONENT OF GROUND ACCELERATION

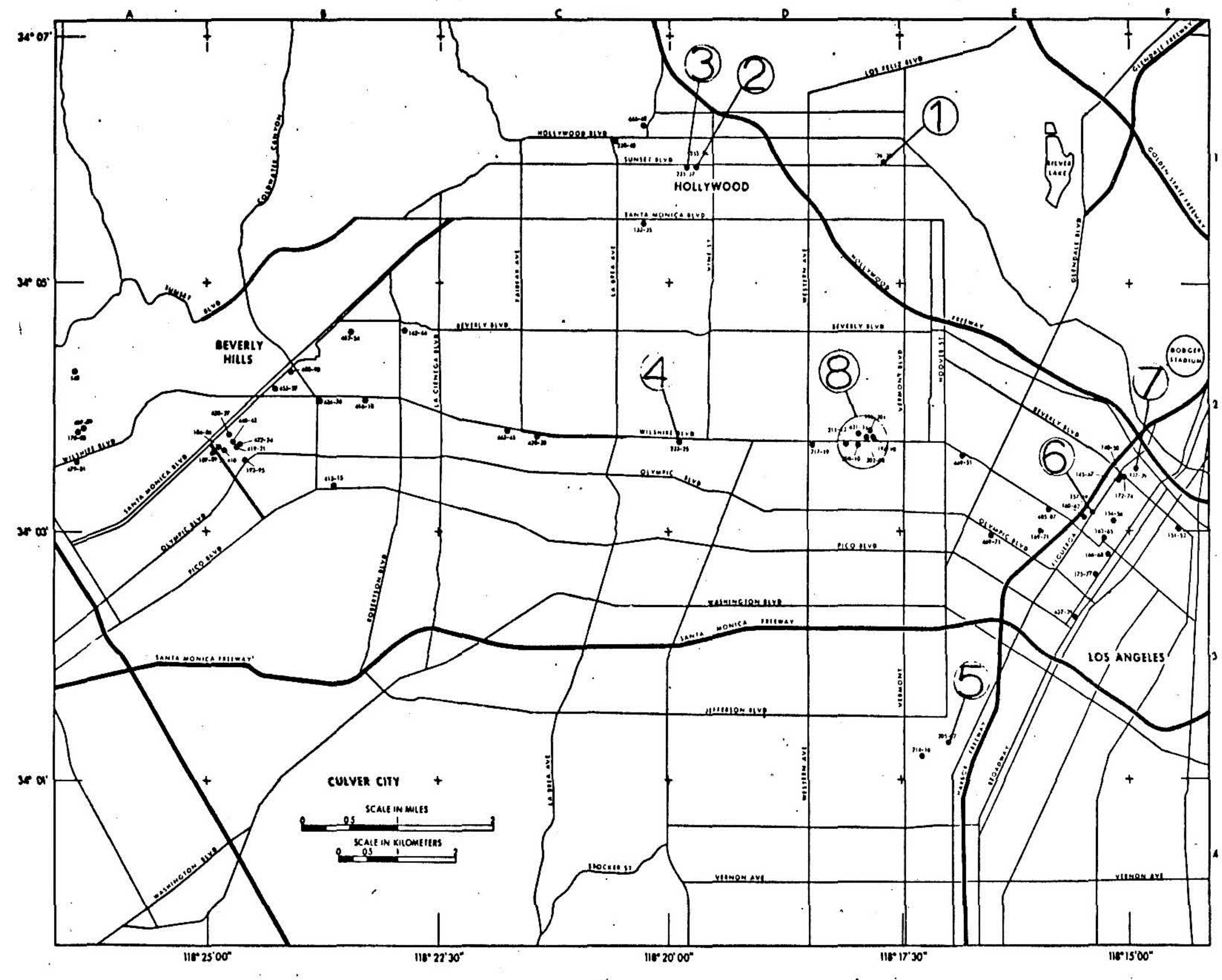
0.10g

0.20g

0.30g



PEAK GROUND ACCELERATION VERSUS DISTANCE



HOLLYWOOD
BEVERLY HILLS
LOS ANGELES
CULVER CITY
SCALE IN MILES
SCALE IN KILOMETERS
HOLLYWOOD BLVD
SUNSET BLVD
SANTA MONICA BLVD
BEVERLY BLVD
WILSHIRE BLVD
OLYMPIC BLVD
PICO BLVD
WASHINGTON BLVD
SANTA MONICA FREEWAY
JEFFERSON BLVD
VERNON AVE
LOS FELIZ BLVD
GOLDEN STATE FREEWAY
GLENDALE BLVD
HOLLYWOOD FREEWAY
LA CIENEGA BLVD
FAIRFAX AVE
LA BREA AVE
WESTERN AVE
VERMONT
HOOVER ST
FIGUEROA
BROADWAY
HARBOR FREEWAY
ROBERTSON BLVD
COLDWATER CANYON
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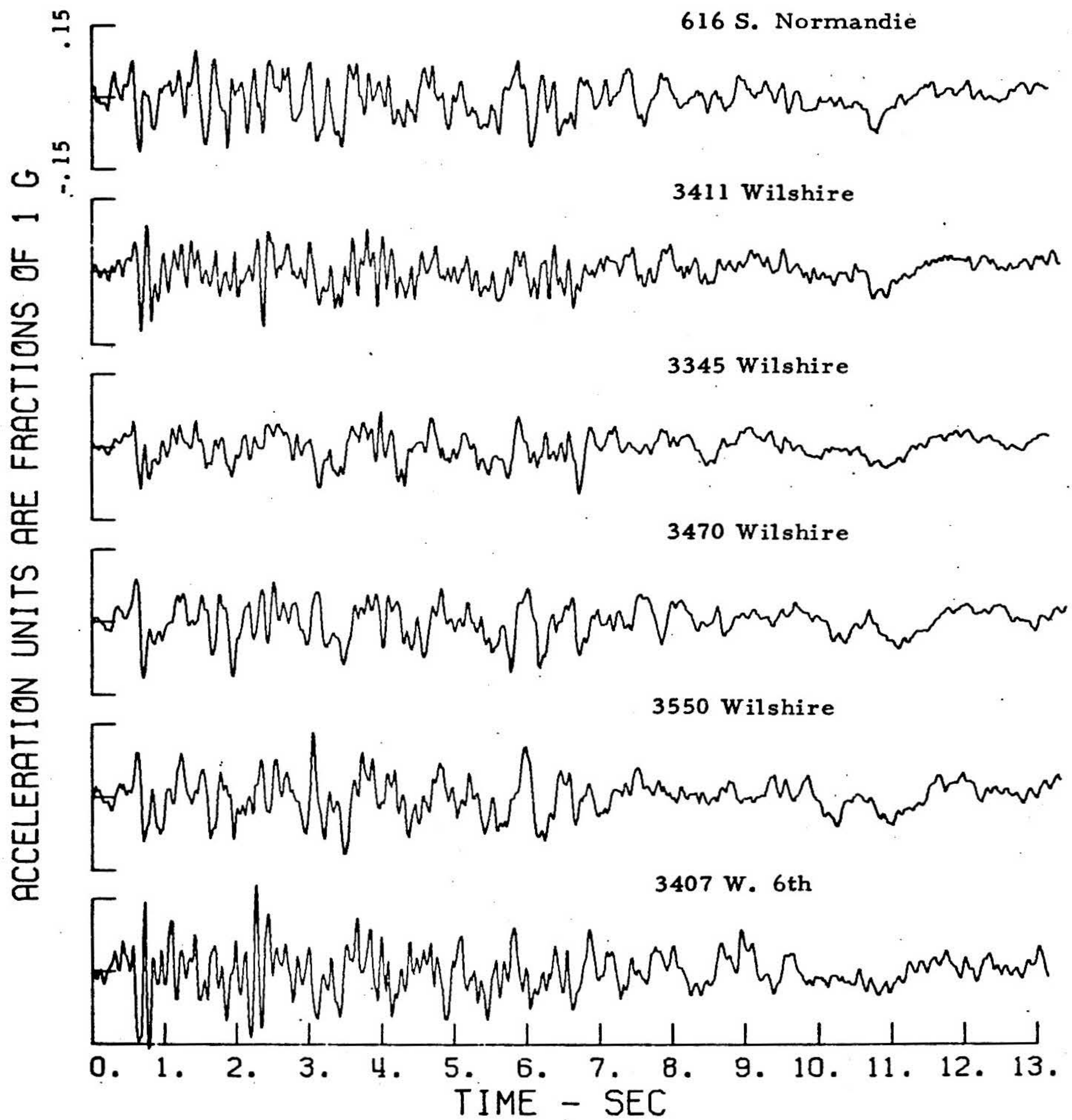
118° 22' 30"
118° 20' 00"
118° 17' 30"
118° 15' 00"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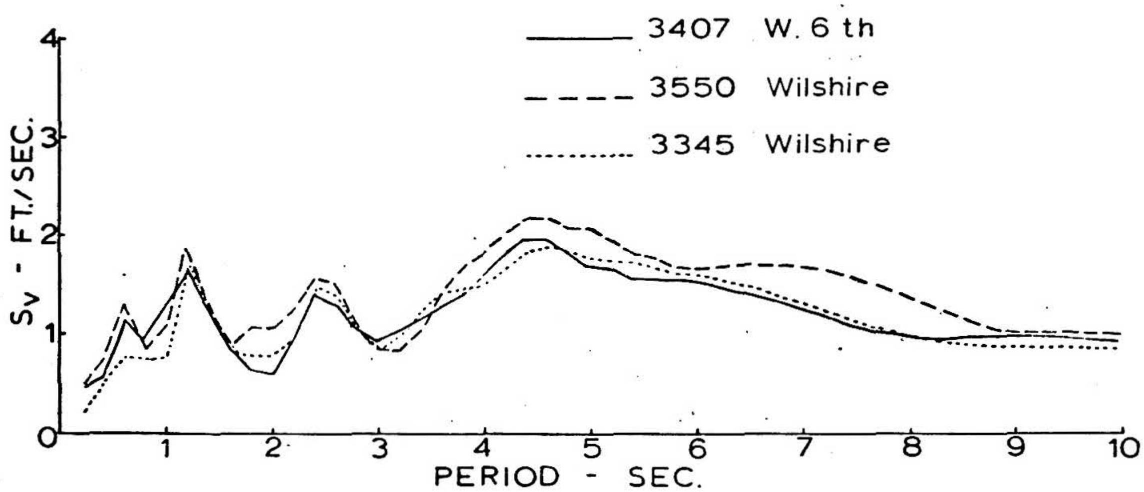

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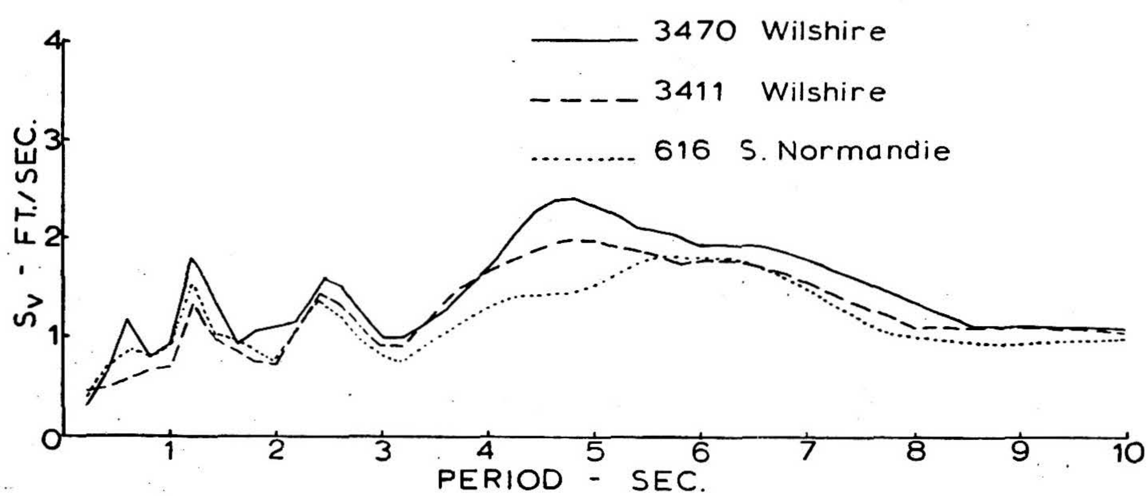

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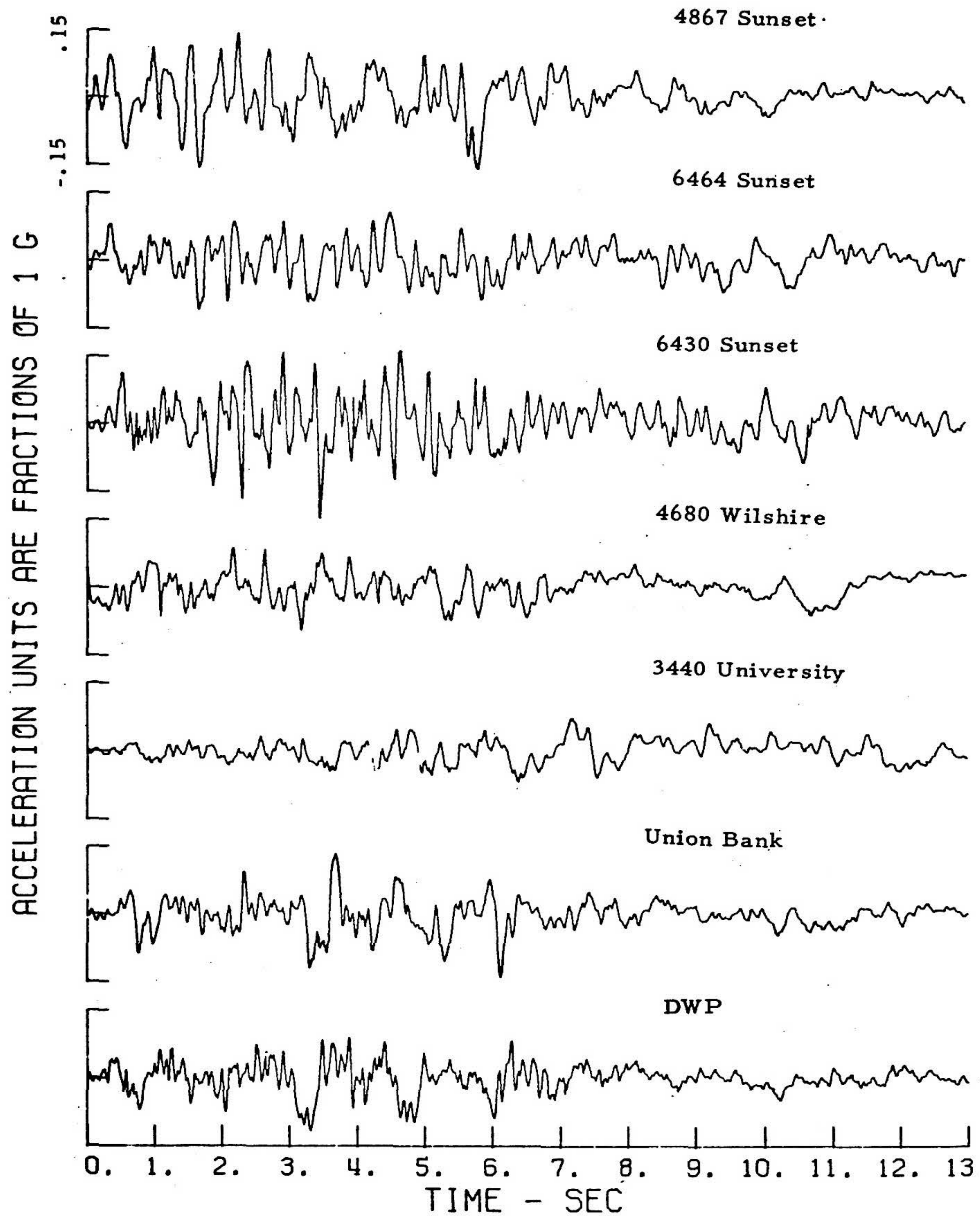
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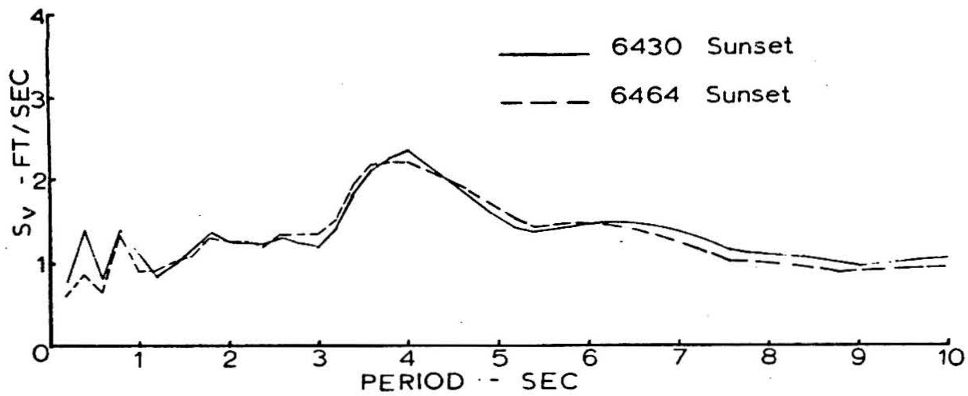
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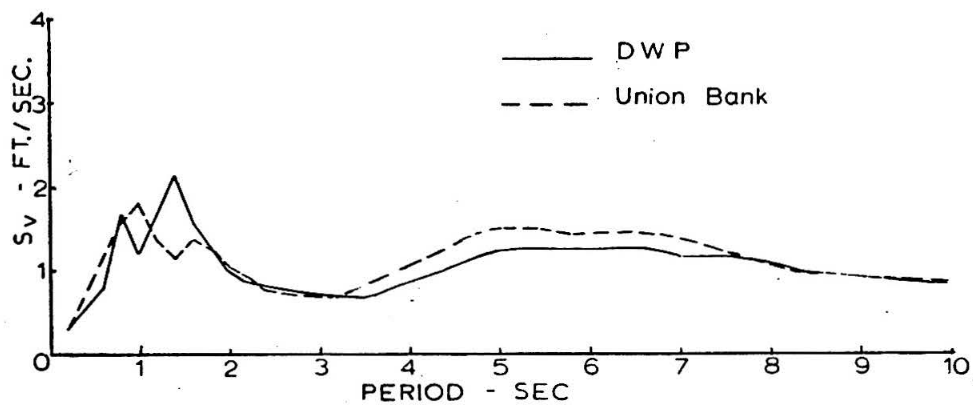
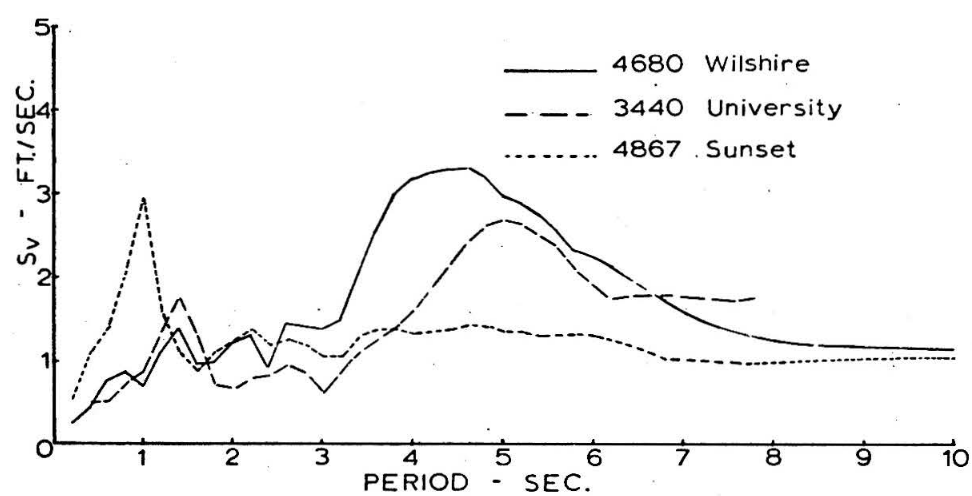
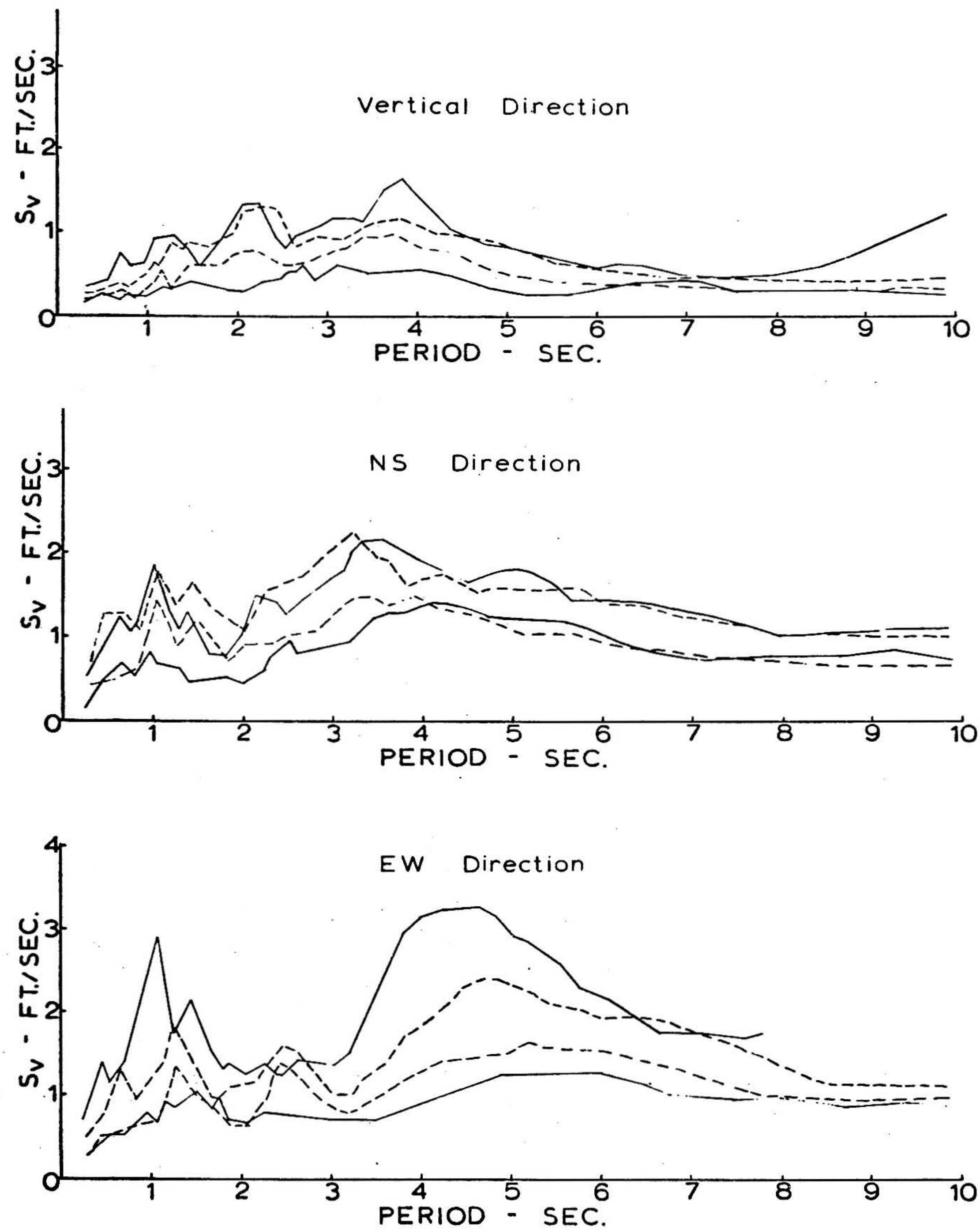
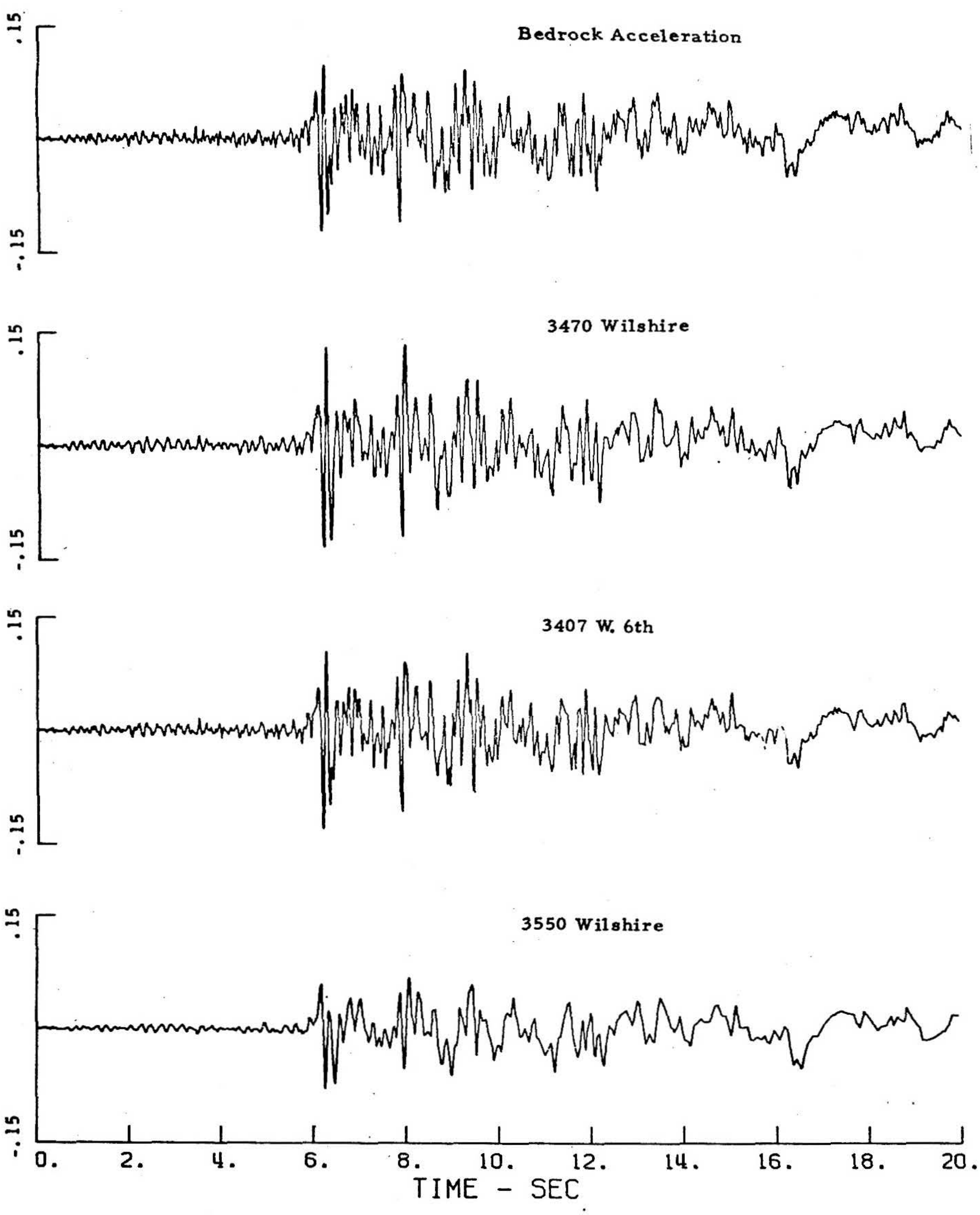
10
PERIOD - SEC


DWP
Union Bank
Sv - FT./SEC.
0
1
2
3
4
1
2
3
4
5
6
7
8
9
10
PERIOD - SEC


4680 Wilshire
3440 University
4867 Sunset
Sv - FT./SEC.
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
PERIOD - SEC.



Vertical Direction
Sv - FT./SEC.
0
1
2
3
1
2
3
4
5
6
7
8
9
10
PERIOD - SEC.
NS Direction
Sv - FT./SEC.
0
1
2
3
1
2
3
4
5
6
7
8
9
10
PERIOD - SEC.
EW Direction
Sv - FT./SEC.
0
1
2
3
4
1
2
3
4
5
6
7
8
9
10
PERIOD - SEC.



Bedrock Acceleration
3470 Wilshire
3407 W. 6th
3550 Wilshire
.15
-.15
0.
2.
4.
6.
8.
10.
12.
14.
16.
18.
20.
TIME - SEC